SPECTROLAB

Development of High Efficiency, Radiation Tolerant, Thin Silicon Solar Cell

JPL Contract 954600

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prepared by

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ABSTRACT

Back surface field cells ranging in thickness from 0.10 to 0.25mm in 0.05mm steps were fabricated. Two ohm-cm cells, 0.15mm (.006") thick produced an average power output in excess of 80 mW for 2 X 2cm configurations. Power output was independent of cell thickness over the range of 0.15 to 0.25mm for all silicon base resistivities used.

Textured cells 0.05mm (.002") thick were produced in 2 X 2cm size which delivered power outputs as high as 62mW for non-field types and in excess of 67mW when back surface field processing was employed. Reinforced perimeter configurations as thin as 0.020mm were produced with polished and textured surfaces.

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1.0 Summary

A twelve element matrix composed of 2 X 2cm textured back surface field cells of varying resistivity (2-100 ohm-cm) and thickness (0.10-0.25mm) were fabricated and delivered to JPL for evaluation. Outputs ranging up to 81mW were observed and power was independent of silicon thickness from 0.15 to 0.25mm for all resistivities employed.

One hundred two ohm-cm textured 2 X 2cm cells 0.05mm thick were fabricated and delivered to JPL during this period. Cell weight, including contacts, was below 60mg, and this lot had an average output power of 57mW with the best cell delivering 62.4mW. Some 0.05mm devices were made using back surface field processing and they produced ten to fifteen percent more power than the cells prepared for delivery. Some of these very thin cells showed evidence of severe warping due to the mismatch in expansion coefficients between the contact material and the silicon.

Ten samples of our reinforced perimeter structure were also made and delivered to JPL. These parts consisted of a narrow (0.75mm) border approximately 0.20mm thick bounding a 0.02mm silicon center section. This structure can be easily handled and shows great promise as a method for large scale production of very thin silicon cells.

2.0 Introduction

The purpose of this program is to develop the necessary technology to produce very thin (0.10mm maximum), high output (17.5 mW/cm^2), silicon solar cells which will display improved radiation performance compared to present state-of-the-art devices. The major emphasis shall be in the areas of back surface field and selective etch technology. Higher resistivity (50 ohm-cm) silicon than is normally used for space flight cells will be investigated as a method for achieving the radiation objectives which are targeted as 15.5 mW/cm^2 after 3×10^{14} equivalent 1 MeV electrons /cm^2 and 14.0 mW/cm^2 after 1×10^{15} electrons/cm^2.

3.0 Technical Discussion

3.1 Back Surface Field (BSF) Matrix

A sixty cell matrix consisting of four thicknesses and three resistivities was produced. The field was incorporated into these cells using aluminum paste which was applied by screen printing techniques. This method has been described in some detail in the Second Quarterly Report of this contract. All cells were diffused using phosphine gas as the junction forming dopant source. Sheet resistances of 120 ohms/square, corresponding to a junction depth of $\sim$0.12 μm were obtained for these samples. The cells were contacted using tantalum-palladium-silver front contacts and chromium-palladium-silver for the back surface metallization. The contact configuration, consisting of a 1.0mm wide collector bar and 12 grids/cm, was deposited by electron beam evaporation through bimetallic masks. Tantalum pentoxide (Ta_2O_5) was used as the antireflection coating. These cells did not have ultraviolet rejection filters. All cells were electrically tested under AMO conditions (135.3mW/cm^2) at 25°C. Table 1 is a summary of the electrical properties of these cells.

It can be seen that there is no statistically significant difference in cell output for cell thicknesses between 0.15 and 0.25mm. In fact the high end range of the thinnest cells (0.10mm) overlaps the range for the thickest cells in some cases. The variation in thickness within any sample group was tightly controlled to $\pm$ 0.012mm. This was verified by weighing the individual samples and calculating the silicon thickness knowing the weight of the contact metal.

One sample from each element of the matrix was randomly selected for spectral response measurements. Table 2 shows the data obtained from these twelve cells.

Table 1

Electrical Properties of BSF Matrix

Thickness (mm)	Resistivity (ohm-cm)	I_{sc} (mA)	V_{oc} (mV)	P_{max} (mW)
0.10	2	159-162.5	600-608	76.5-78.3
0.15	2	163.5-165	609-612	81.1-81.6
0.20	2	165-167.5	607-612	78.3-80.3
0.25	2	160-164.5	608-613	78.5-80.3
0.10	10	159.5-160.5	600-606	76.5-77.3
0.15	10	161.5-165	600-605	76.8-77.8
0.20	10	163.5-166	602-605	78.1-79.4
0.25	10	163.5-165	602-608	77.3-78.3
0.10	100	161.5-165.5	588-605	72.5-77.3
0.15	100	163-165.5	599-604	76.0-77.5
0.20	100	165-167.5	594-597	75.5-77.0
0.25	100	166-166.5	601-603	76.0-78.0

TABLE 2

BSF CELL MATRIX SPECTRAL RESPONSE (SINGLE SAMPLE) $\mu A/\mu W$

Filter / Cell Type	.4μ	.45μ	.5μ	.55μ	.6μ	.65μ	.7μ	.75μ	.8μ	.85μ	.9μ	.95μ	1.05μ
0.10mm 2Ω-cm	.14	.31	.40	.44	.47	.51	.55	.60	.64	.71	.74	.74	.30
0.15mm 2Ω-cm	.14	.31	.40	.44	.47	.51	.55	.60	.64	.72	.75	.81	.37
0.20mm 2Ω-cm	.14	.31	.40	.44	.47	.51	.56	.61	.65	.73	.77	.86	.44
0.25mm 2Ω-cm	.14	.31	.39	.43	.46	.51	.55	.60	.65	.72	.76	.88	.48
0.10mm 10Ω-cm	.14	.31	.39	.43	.46	.51	.55	.60	.65	.73	.75	.73	.28
0.15mm 10Ω-cm	.14	.31	.39	.43	.46	.51	.55	.60	.65	.73	.77	.82	.35
0.20mm 10Ω-cm	.14	.31	.39	.44	.47	.51	.55	.60	.65	.73	.78	.90	.46
0.25mm 10Ω-cm	.13	.29	.39	.43	.46	.50	.55	.60	.64	.72	.77	.90	.51
0.10mm 100Ω-cm	.14	.30	.39	.43	.46	.50	.54	.59	.63	.70	.72	.70	.30
0.15mm 100Ω-cm	.14	.30	.39	.43	.46	.50	.54	.59	.63	.70	.72	.75	.34
0.20mm 100Ω-cm	.13	.30	.39	.43	.46	.50	.54	.59	.63	.70	.72	.81	.40
0.25mm 100Ω-cm	.14	.30	.39	.43	.46	.50	.54	.59	.63	.70	.73	.84	.45

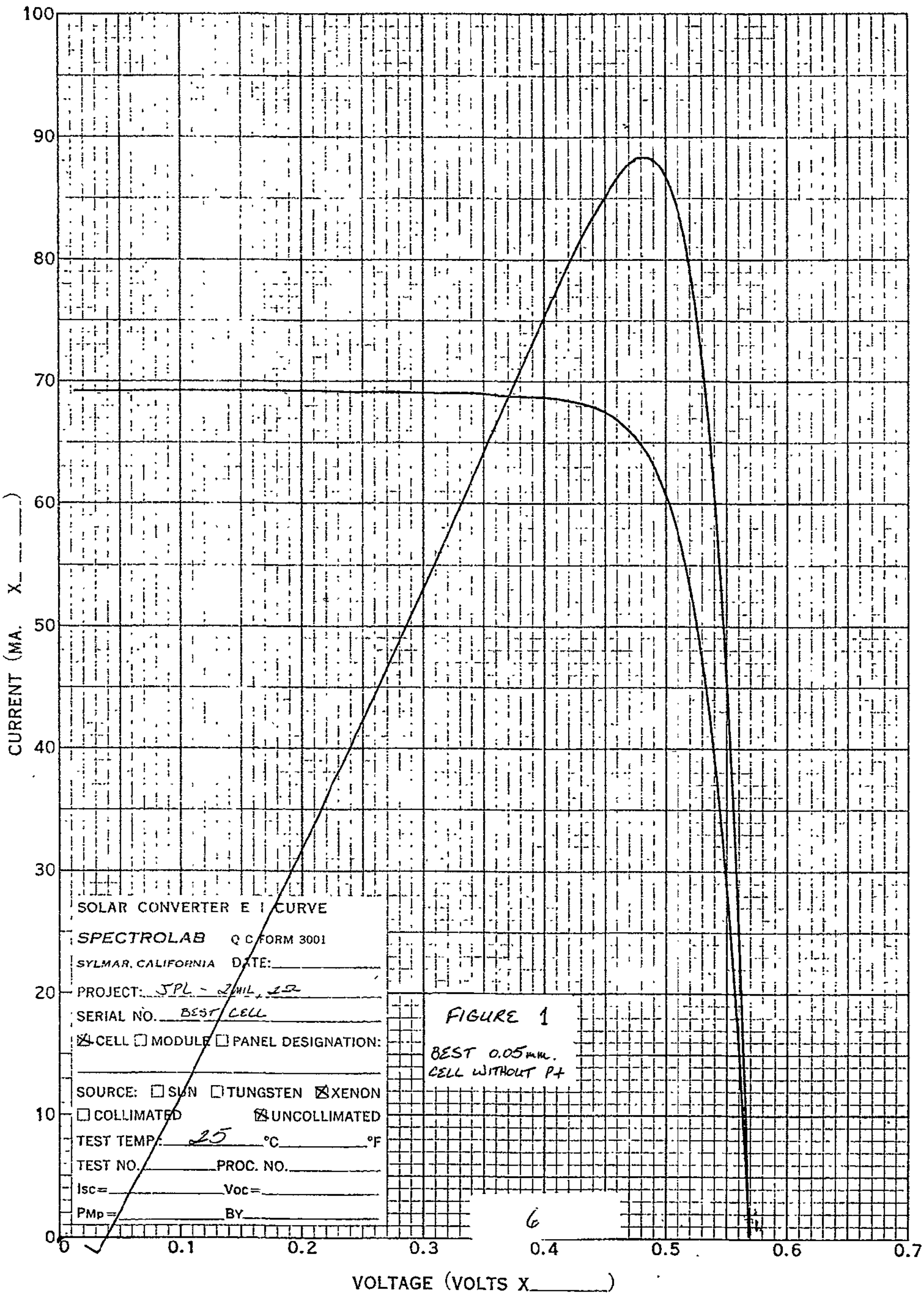
The influence of cell thickness was not evident for wavelengths equal to or less than 800 nm, and did not become pronounced until 950 nm. The 0.10mm cells showed very little difference in long wavelength response as a function of base resistivity. The fact that the high resistivity 0.25mm cell had a lower response than either the ten or two ohm-cm cell of the same thickness is probably an anomoly caused by the sampling method used.

3.2 Thin (0.05mm) Cell Fabrication

A one hundred piece lot of texturized, 0.05 mm thick cells was completed during this month. This lot was composed of cells from a variety of fabrication schemes to test the effects of silicon blank preparation, back contact metallization variations, contact application tooling and back surface reflectors. The average cell output was approximately 57mW at 25°and the highest output was 62.4 mW as can be seen in Figure 1. The average cell mass was 57 mg of which approximately 15 mg was contact metallization.

3.2.1 Effect of Silicon Blank Preparation

The silicon slices used for production of 0.05 mm cells were obtained by either etching an oversize 2 X 2 cm part or dicing a 2 x 2 cm blank from a thinned round wafer. The latter technique is necessary if the aluminum paste technology for back surface fields is employed. In either of the above two cases it was found that lapping to remove blade marks from sawing was not necessary. Blade marks are rarely more than 0.006 mm in amplitude and they do not significantly affect the handling properties of thin cells. If an oversize 2 X 2 blank is to be thinned, a one-step etch in sodium hydroxide is used to assure squared edges. This leaves a surface which might be best described as waffled or "orange-peel" in appearance. If the wafer is cut from an oversize round, two possible surface finishes are possible. The first is the "orange-peel" surface described above and the other is the polished surface obtained by using solutions of nitric-hydrofluoric and acetic acids either alone or followed by the hydroxide etch. Comparisons of the mechanical properties of these two surface finishes both before and after texturizing failed to show any significant advantage in handling.


CURRENT (MA. X____)
VOLTAGE (VOLTS X____)
0
10
20
30
40
50
60
70
80
90
100
0.1
0.2
0.3
0.4
0.5
0.6
0.7
SOLAR CONVERTER E I CURVE
SPECTROLAB Q C FORM 3001
SYLMAR, CALIFORNIA DATE:
PROJECT: JPL - 2MIL, 22
SERIAL NO. BEST CELL
☒ CELL ☐ MODULE ☐ PANEL DESIGNATION:
SOURCE: ☐ SUN ☐ TUNGSTEN ☒ XENON
☐ COLLIMATED ☒ UNCOLLIMATED
TEST TEMP: 25 °C °F
TEST NO. PROC. NO.
Isc= Voc=
PMp= BY
FIGURE 1
BEST 0.05mm. CELL WITHOUT P+

Because of its size and flexibility, the 2cm X 2 cm blank of 0.05 mm thickness is nearly as resistant to fracture as thicker parts of the same area. In the case of larger area parts of the same thickness there was a higher incidence of breakage which occurred most frequently during tweezer handling. The forceps would induce a torsion at the edge causing a fracture which readily propagated across the wafer. To overcome this problem edge reinforcement was examined. Several techniques were found to be successful. The actual wafer edge thickness could be increased by fusing a silicon border to the wafer. This was achieved by using an aluminum foil preform between the wafer and reinforcing silicon and heating in an inert atmosphere to a temperature in excess of 577^{o}C.

A more direct approach involved thinning the center section. This could be done using chemical etching or mechanical abrasion. The use of acids proved to be ineffective for thin slices since the acid etched most rapidly at the interface between the wafer and resist. When the center section was thinned to 0.05 mm, it would frequently fall away from the border. Both the hydroxide etching and abrasive techniques avoided this problem. Base etching was accomplished with sodium hydroxide in 30% concentration at a temperature of 105^{o}C and abrasive etching utilized a highly controllable silicon wafer abrasion machine, which is commercially available. Subsequent chemical etching to thin the wafer was found to be adequate for removal of the lattice damage caused by abrasive etching even at the highest rates of removal (25μm/minute). This latter technique was successfully employed in the production of 0.05 mm cells with a back surface field.

3.2.2 Back Contact Metallization on 0.05 mm Cells

Cells of 0.05 mm thickness which were contacted using the conventional titanium-palladium-silver or chromium-palladium-silver back metallizations warped severely after sintering. This was due to the quantity of silver (3-4μm) deposited which is not matched in expansion coefficient with silicon. It was possible to avoid this problem by applying a thinner layer of silver ($\sim$1μm), sintering, and then building up the silver thickness in a second deposition step which did not require any further heat treatment.

Several successful alternatives were also devised. An aluminum-silver contact was used which did not require higher temperatures to achieve an adherent, ohmic contact. A molybdenum-palladium-silver system was successfully used in which 2 to 3 μm of molybdenum provided the electrical conductivity and good expansion match to silicon and the silver thickness could correspondingly be reduced. Finally, a grid configuration back contact was tested which helped eliminate warping and reduced total cell weight.

3.2.3 Contact Application Tooling

Two approaches to contacting 0.05 mm cells were examined. One involved the use of conventional bimetallic masking and cell holders, and the other used bimetallic masks on round wafers from which a 2 X 2 cm part would later be diced. The latter technique was abandoned when it was found that substantially fewer wafers could be contacted in a single pump-down and the dicing operation caused a slight power loss. The one hundred, 0.05 mm cell complement sent to JPL was contacted in the standard frames but a number of cells had poor curve shape due to contact metal being deposited over the cell edge. Attempts to clean the metal from the edges resulted in cell fracture due to the fragile nature of these thin devices. New tooling has been ordered with optimized grid spacing and locators which should eliminate this problem.

3.2.4 Back Surface Reflector

To investigate the possibility of utilizing longer wavelength radiation with thin cells, a matrix of 0.10 mm thick, 1.5 ohm-cm cells was prepared. The back of the cell was either polished or texturized and was contacted with one of several different metals. A slight advantage accrued to the smooth surface in terms of short circuit current gain with an apparent further increase observed for an aluminum metallization.

3.3 Perimeter Reinforced Thin Silicon Slices

The edge protected, hydroxide etching technique discussed in 3.2.1 was used to prepare silicon slices in the form of 2 X 2 cm squares with a center section 0.025 mm thick and a border 0.20 mm thick and 0.75 mm wide. The average wafer mass was 47.7 mg of which 28.3 mg was attributable to the border thickness. This implies an average center section thickness of 0.022 mm. Slices as thin as 0.006 mm were readily prepared using this technique. This configuration could be easily handled without fracturing the silicon.

The reinforced perimeter configuration prevents severe cell warping caused by contact metallization, allows standard handling and interconnect procedures to be used, and can be used for fabrication of thin wrap-around contact cells. Such a cell necessarily requires thick edges to allow the use of dielectric pastes, which typically have poor expansion matches with silicon. At present a number of such wafers have been prepared and have aluminum back contacts which remain from the field incorporation step. It was found best to leave the aluminum in place for good dielectric adherence. Several thick film dielectric materials are now being tested to ascertain the optimum combination of firing times, thicknesses and number of individual layers required for a pinhole-free layer of glass.

3.4 Production of 0.05 mm BSF Cells

A 0.05 mm, 10 ohm-cm, back surface field 2 X 2 cm cell yeilded 67.6 mW at 25°C as shown in Figure 2. This cell was prepared from a round wafer with a thick border. This type of cell will be used with an optimized grid configuration and a weld pad collector bar for the next delivery of 0.05 mm cells to JPL.

4.0 Conclusions

With new tooling and further process optimization, it may be possible to mass produce 0.05 mm cells with AMO efficiencies approaching thirteen percent.

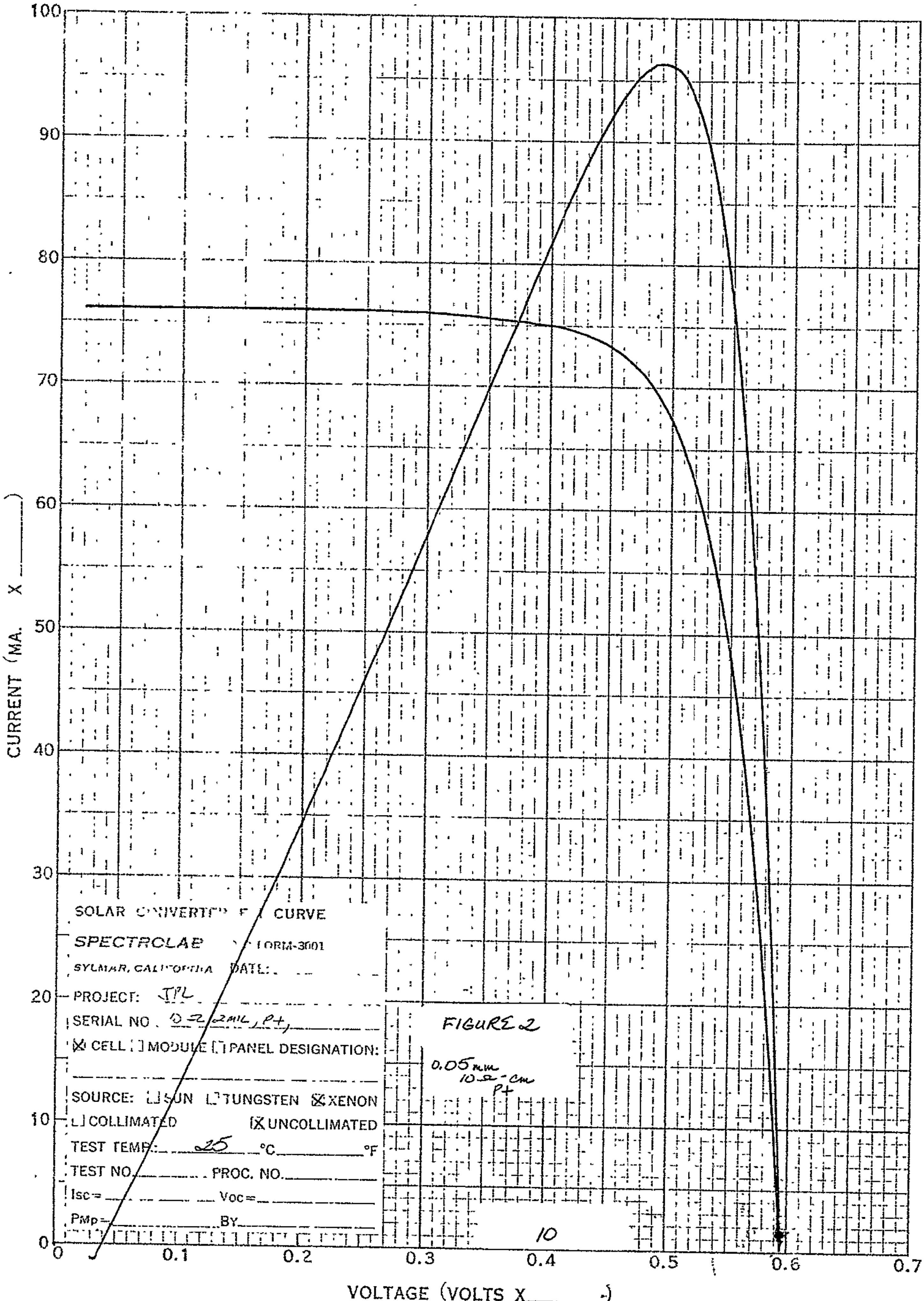
5.0 Recommendations

Spectrolab recommends the deletion of two hundred solar cells of 0.01cm thickness of highest available resistivity from the delivery schedule and substitution of 0.15 mm, 2 ohm-cm BSF cells and reinforced perimeter cells with center section thicknesses of 0.025 mm.

6.0 New Technology

Spectrolab has no new technology to report at this time.

7.0 Projected Work - Next Three Months


CURRENT (MA. X ____)
VOLTAGE (VOLTS X____)
0
10
20
30
40
50
60
70
80
90
100
0.1
0.2
0.3
0.4
0.5
0.6
0.7
SOLAR CONVERTER E I CURVE
SPECTROLAB
FORM-3001
SYLMAR, CALIFORNIA
DATE:
PROJECT: JPL
SERIAL NO. 10 Ω 2MIL, P+,
[X] CELL [ ] MODULE [ ] PANEL DESIGNATION:
SOURCE: [ ] SUN [ ] TUNGSTEN [X] XENON
[ ] COLLIMATED
[X] UNCOLLIMATED
TEST TEMP: 25 °C °F
TEST NO. PROC. NO.
Isc = Voc =
PMP = BY
FIGURE 2
0.05 mm
10 Ω-cm
P+
10

The next three months will see the completion of this contract and the delivery of the following devices:

1. Eighty process integration matrix cells presently awaiting tooling delivery.
2. Two hundred 0.05 mm cells also awaiting tooling delivery.
3. Twenty wrap around cells.
4. Two hundred evaluation cells from pilot line production.